The Evolution of Protoplanetary Disks: A Decade of HST Coronagraphy

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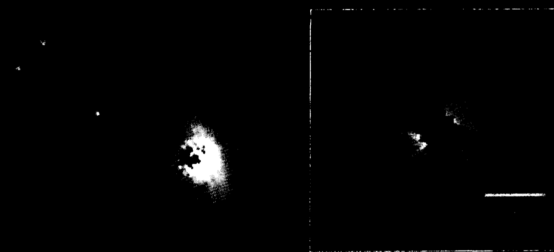
In the Spirit of Bernard Lyot, Berkeley CA June 2007

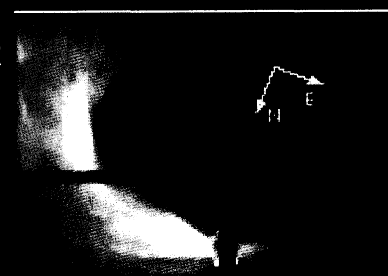
Why Protoplanetary Disks in a Meeting on Exo-Planets and Debris Disks?

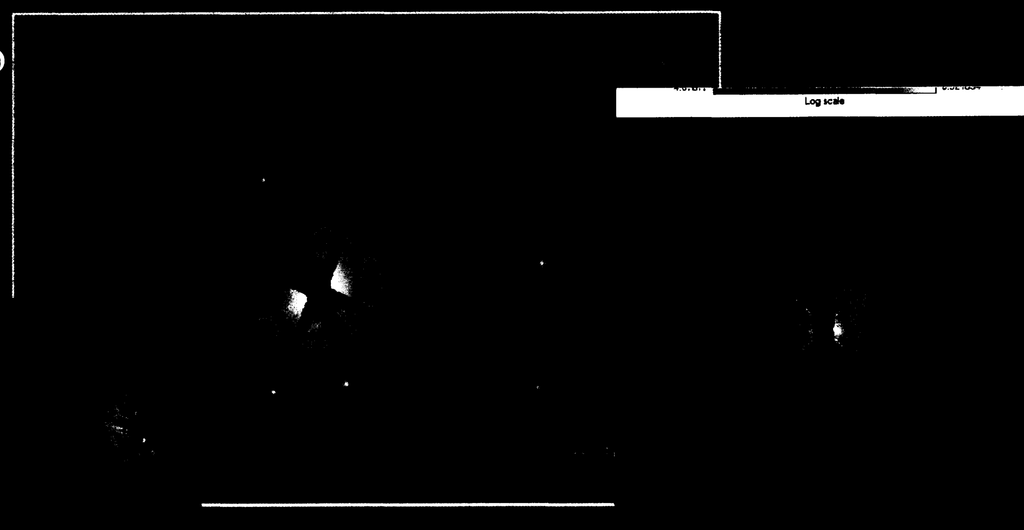
- These are the evolutionary precursors of debris disks,
- The places where gas giant planets form,
- The place where volatile rich planetesimals are produced which can deliver organics and water to terrestrial planets

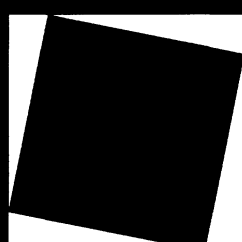
Protoplanetary Disks

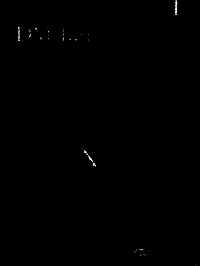


- Gas rich disks, detectable in CO
- Larger fractional IR excess than debris disks,
- Disk is optically thick, so scattered light imagery probes the disk surface, not its total mass
- Age range spans ~1 Myr to ~10 Myr, overlapping with central clearing.



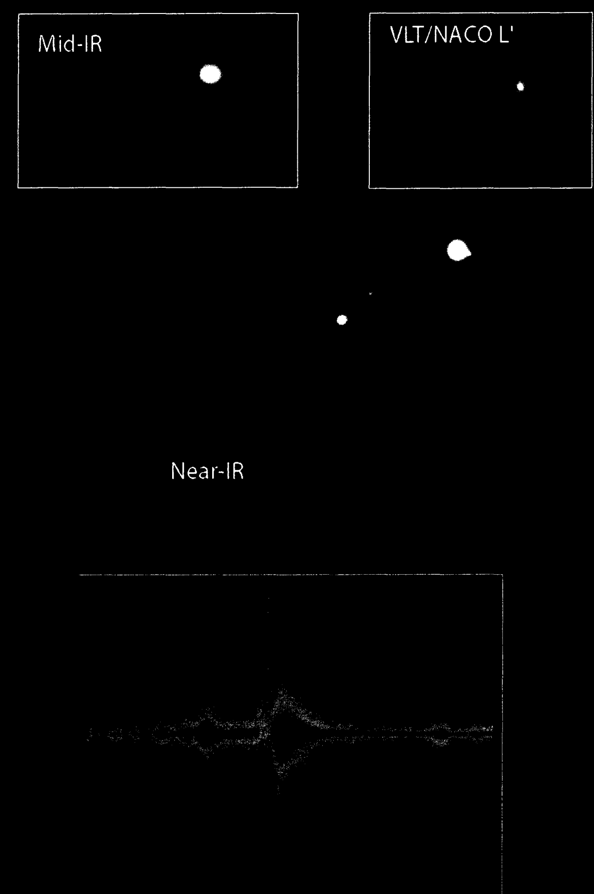






Binaries

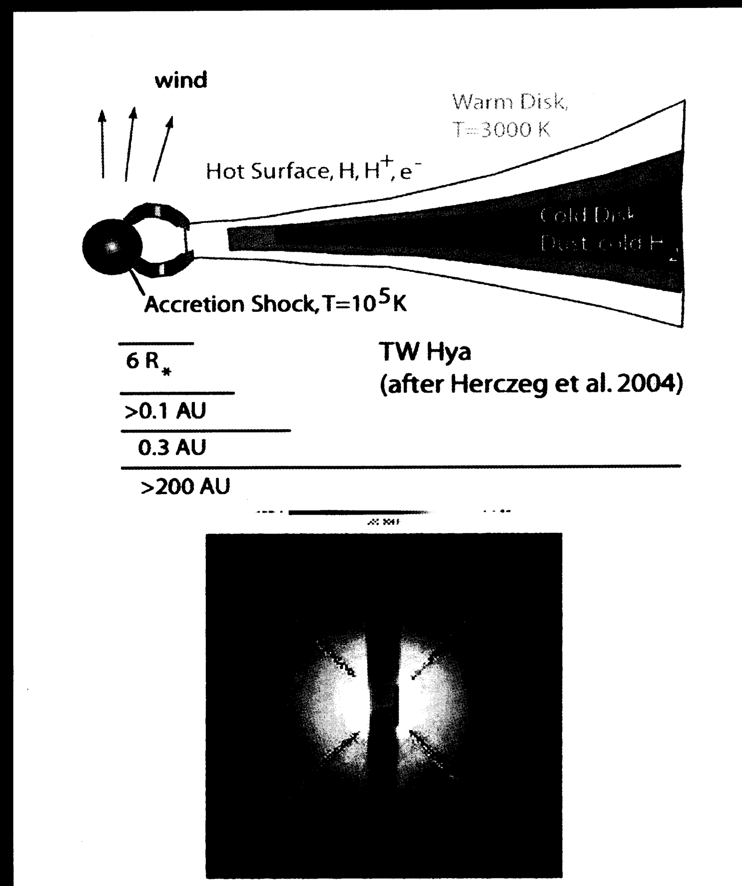
- Majority of HST coronagraphic imagery devoted to single stars
- Bright circumbinary disks observed (GG Tau) both with HST direct imagery (Krist et al. 2002) and with coronagraphy (McCabe et al. 2002), UY Aur (Hioki et al. poster)
- However, for the 1-1.5" separation binaries observed to date, the IR excess is typically associated with the primary, and the disk is frequently small.



HD 104237A+ association
Grady et al. (2004)

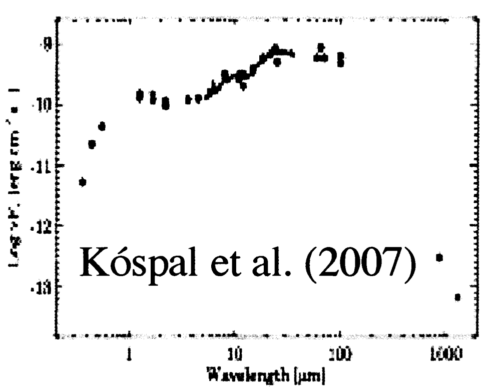
Theoretical Expectations

- Initial expectation is that gas and dust should be well-mixed in the disk
- For ISM-like dust grains, this leads to the disk assuming a flared structure (Chiang & Goldreich 2000; Natta & Whitney 2000)

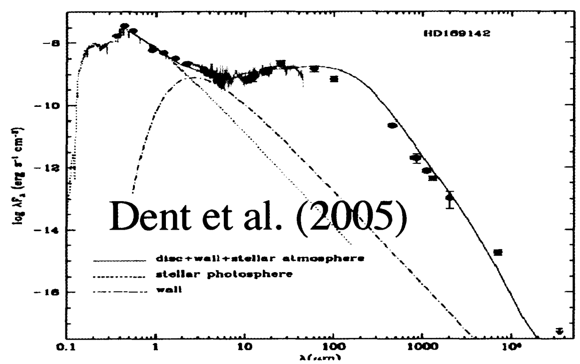


Expected Evolutionary Sequence

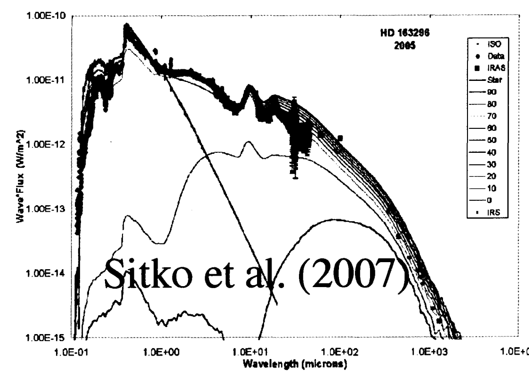
Par 21 YSO



HD 169142 Meeus Ib



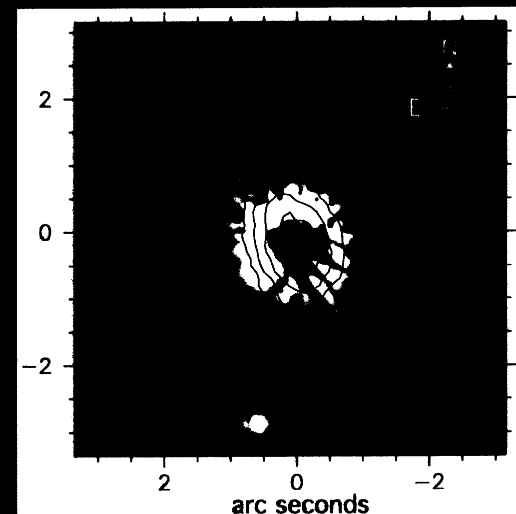
HD 163296 Meeus IIa

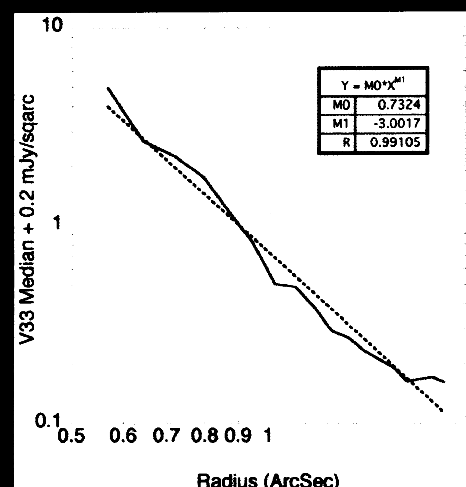


- SEDs classified according to shape (Meeus et al. 2001)
- Expect to go from YSOs to Meeus I (flared disk, following Dullemond & Dominik 2004a,b) to Meeus II (flatter, shadowed disks) as a result of grain growth and settling, with the next step dissipation of the gas and the transition to debris disks. Expect that young disks should be bright and have SB $\propto r^{-2}$.
- Expect that accretion should ramp down, and mass loss via collimated jets should be limited to the youngest systems: accretion rates for Meeus I SED sources should be higher than for Meeus II, and these disks should be younger.

HD 169142

- A8Ve Herbig Ae star at d=145 pc
- Meeus Ib, no warm silicate emission
- Resolved in cold CO (Raman et al. 2006)
- NICMOS data shows 200 AU disk (1.4”)
- Radial surface brightness $\propto r^{-3}$
- Outer disk is constant opening angle, not flared

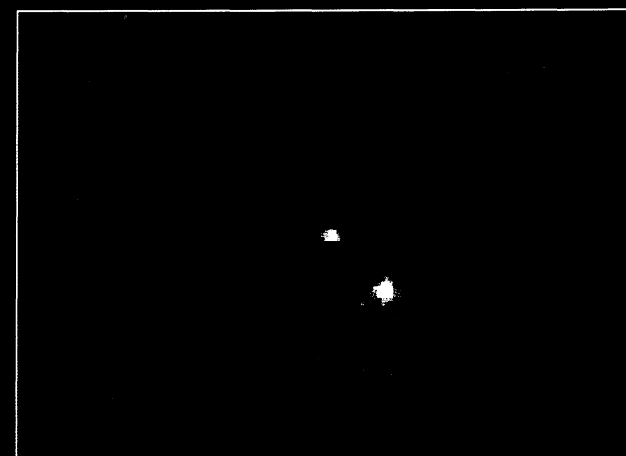




CO contours (Raman et al. 2007), NICMOS (Grady et al. 2007)

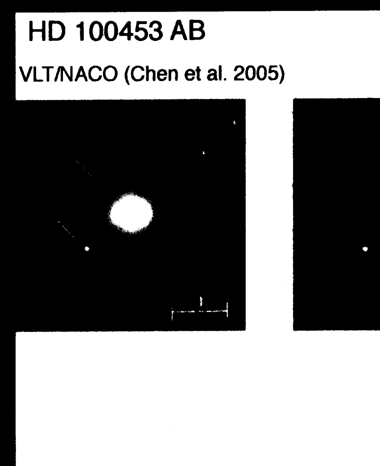
The Inner Disk of HD 169142

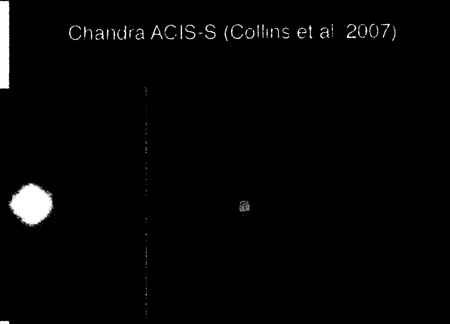
- Chandra ACIS imagery demonstrates that the Herbig Ae star resembles ZAMS early F stars - stellar activity rather than accretion
- No jet is seen; current upper limit on accretion rate is $7 \times 10^{-10}\ M_{\odot}\ yr^{-1}$.
- No warm CO (Brittain, priv. comm.)
- Companions date this system to 6± 3 Myr - on the old side of the Herbig Ae population.
- Central cavity in disk to ~40 AU; larger than can be accounted for by photo-evaporation models - dynamical source is suspected.



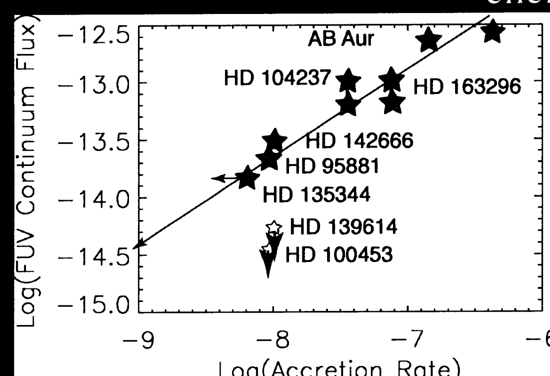
HD 169142 is not unique

- HD 100453 is similar, with a lower upper limit to accretion (Collins et al. 2007)
- HD 100546 (Grady et al. 2001), HD 97048 (Doering et al. 2007) have similar radial SB profiles.
- Upper limit to HD 100546's accretion rate is $1 \times 10^{-9}\ M_{\odot}\ yr^{-1}$ from the continuum near Lyα, and from FUSE data.
- Common feature appears to be presence of central cavities in disks.





Chandra ACIS-S imagery color-coded by energy (Collins et al. 2007)

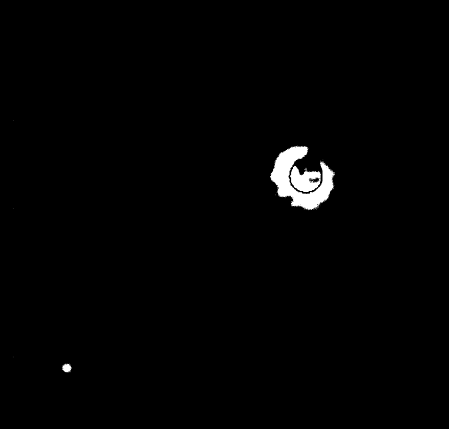


Discrepant measures of accretion from Brγ and In the FUV pinpoint other stars with little accretion. IR data from Garcia Lopez (2006)

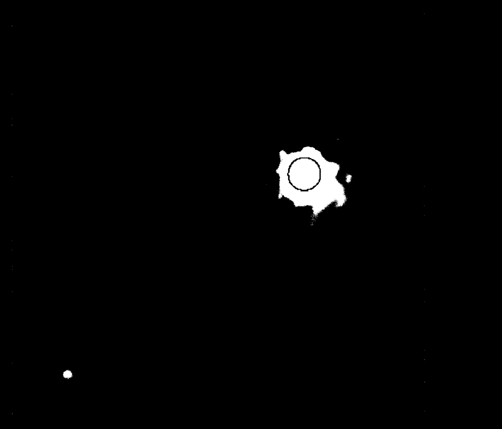
The Stranger Case of HD 135344

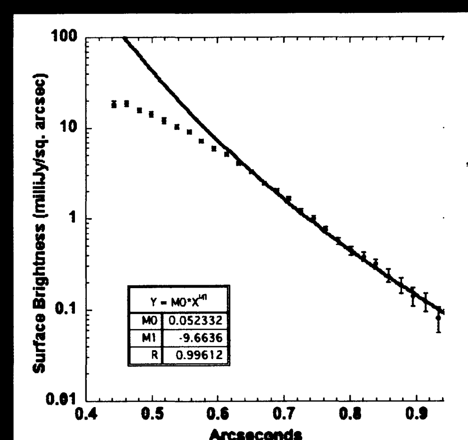
- F4Ve, d=145 pc, t~8 Myr
- FUV data indicate that the star is accreting at $3x10^{-9}$ $M_{\odot}$ yr^{-1}.
- Outer disk detected at 1.1 and 1.6 µm
- Radial SB unexpectedly steep: $r^{-9.6}$: outer disk is in deep shadow
- NIR excess large, especially for accretion rate
- No resolved stellar companion in NIR.
- Structure in SED suggests developing cavity
- Also not unique: HD 142527 has similar SB(r) (Fukagawa et al. poster).

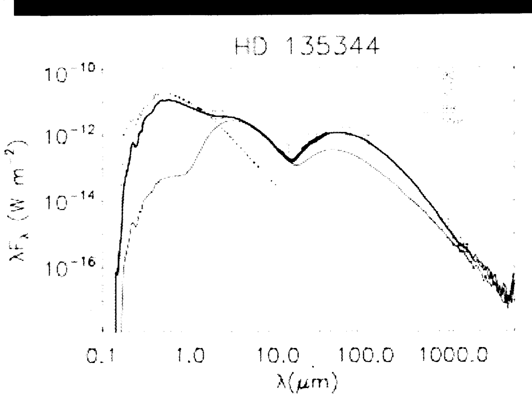
1.1µ m



1.6 µm

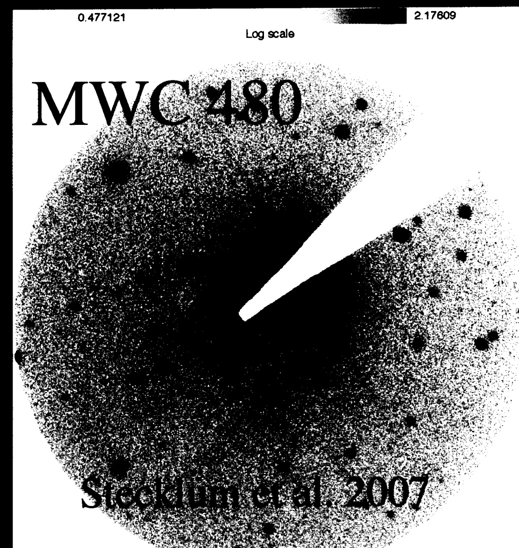


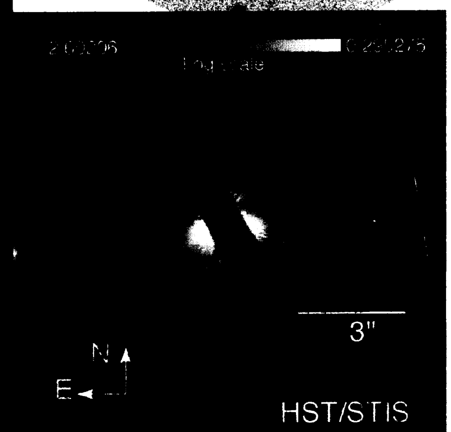


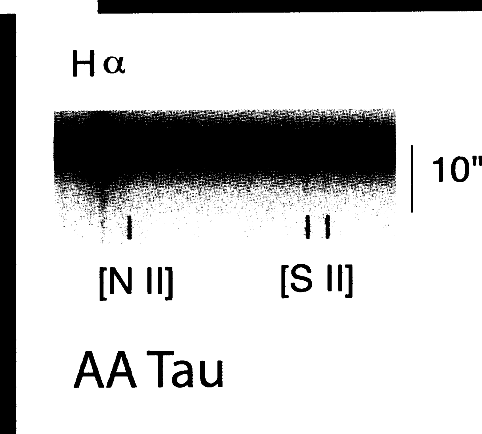


Meeus Group II

- Majority of the STIS T Tauri stars
- Jets are common for both Herbig Ae and T Tauri stars
- Accretion rates span 10^{-7} to 3×10^{-9} $M_\odot$ yr^{-1}, accretion to at least 7 Myr.
- Dated Herbig Ae stars in this group are younger than the majority of the Meeus I sources.
- SB(r) ranges from r^{-3} (HD 163296, Wisniewski et al. 2007, poster) to $r^{-5.1}$ (MWC 480) to ?
- For disks like MWC 480, keeping the disk in shadow at a low accretion rate requires that the disk is rather flat.
- General characteristic - seen in T Tauri stars - grain growth and settling is a disk-wide phenomenon.







Cox et al. (2005), O'Sullivan et al. (2005)

Lessons Learned

- Coronagraphic imagery of the disk is crucial in constraining modeling of the IR data.
- Majority of Meeus I sources have disks as flat as the Meeus II sources: they are bright in scattered light because they lack inner disk material.
- Dust settling and growth precedes the end of accretion; the end of accretion does not appear to be linked to running out of gas, but may be linked to formation of large bodies in the disk.

Implications for Future Instruments and Missons

- The smaller the IWA the better.
- Measurement of disk outer radii depends on a FOV sufficient to ensure that there is a firm sky detection. Similar needs for zodi detection.
- Disks and planetary systems exist in context: a sufficient field of view to image the full system and nearby companions is crucial for the interpretation of particular systems.
- Outer disks span a much, much wider range in surface brightness than had been anticipated: need for large intra-scene dynamic range